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LAMPF PRIMARY BEAM LINE PROTECTION SYSTEM*

R. J. Macek, E. W. Hoffman, and O. B. van Dyck+

Abstract

An effective system for the protection of LAMPF primary beam lines has been built and installed. In three years of operations, it has prevented major damage from the effects of very high intensity (up to 600 μA) errant beams. The harsh environment of the target cells poses a major technical problem requiring the design of highly radiation hardened, remotely serviceable components capable of handling high thermal loads often in vacuum. After a brief discussion of general system considerations, the five major subsystems are described including design criteria, special problems encountered in implementation, operational effectiveness and planned improvements.

Introduction

The average power of the LAMPF primary proton beam is presently about 400 kW at 800 MeV and will eventually be increased to 800 kW when the design current of 1 mA is reached. At a typical emittance of 0.5 mrad-mm, the power density is capable of inflicting thermal damage to nearly any beam line component that it strikes in times as short as 100 μs[1]. Particles scattered from pion production targets are also capable of producing thermal damage to components. Excessive radiation doses from scattered beam or from other beam spills may cause radiation damage to components or interfere with the proper functioning of instrumentation. Beam spills may produce unacceptable component activation in areas such as the switchyard that are not designed for remote handling. Rapid loss-of-vacuum accidents, some of which can be beam induced, have damaged beam diagnostic instrumentation such as the harps (secondary emission grids used for profile measurements). Replacement of damaged components is often an expensive, time consuming task requiring remote handling.

System Considerations

Whereas a computer-based system is inherently more flexible, data processing and decision making in the LAMPF beam line protection system are generally achieved with dedicated analog electronics and hard-wired logic elements in order to minimize response times. An exception is the transmission monitor (TM) which evolved from a computerized current monitoring system and remains under computer control.

Signals derived from the various protective devices limit beam currents to safe values through two systems which differ in approach and response times. The "run permit" system is an interlock chain which terminates the beam within tens of milliseconds. Beam injection is withheld until the interlock chain is reset, usually by the control room operator. The "fast protect" system interrupts beam operation at the injector within tens of microseconds. Beam injection is interrupted for the remainder of the macropulse and for as long as the interrupt signal is present. In this way, it limits the average current to a safe level.

A high degree of reliability is achieved through reliable subsystems and by redundancy since most errant beam conditions are detected by more than one device. Reliance on administrative rules or operator response is minimized. Consideration has been directed towards making the system easy to use, diagnose, and maintain while minimizing false alarms which detract from the systems' credibility with operating personnel. For ease of diagnosis, the central control computer acquires data which can be used to quickly identify the devices generating fast protect signals or have opened the run permit interlock chain.

Collimators

Thirteen fixed aperture, multi-purpose collimators are installed in the high intensity primary beam line (line A) downstream of the switchyard. During normal operation, they limit beam halos produced by nuclear and multiple coulomb scattering in production targets as well as the heat load and activation to magnets, beam diagnostics and some vacuum seals. Because the collimators are the limiting apertures of the beam line, they protect more vulnerable and valuable components from damage by errant beams.

A schematic diagram of the collimators and protection instrumentation at a typical target cell (A-2) is shown in Fig. 1. The first upstream collimator is an air-cooled steel device with a large aperture whose function is to prevent beam halo from producing spurious signals on the harp PC board or toroid. The second is a water-cooled, copper collimator to remove remaining halo that could strike the toroid or small harp PC board. The third is a water-cooled tungsten allow collimator that intercepts backscattered radiation from the target. The downstream collimator serves to shield the downstream quadrupole triplet from the high heat load of the nuclear scattered beam from the target. The second and fourth collimators are shown with upstream guard rings which are used for detecting spills on these collimators.

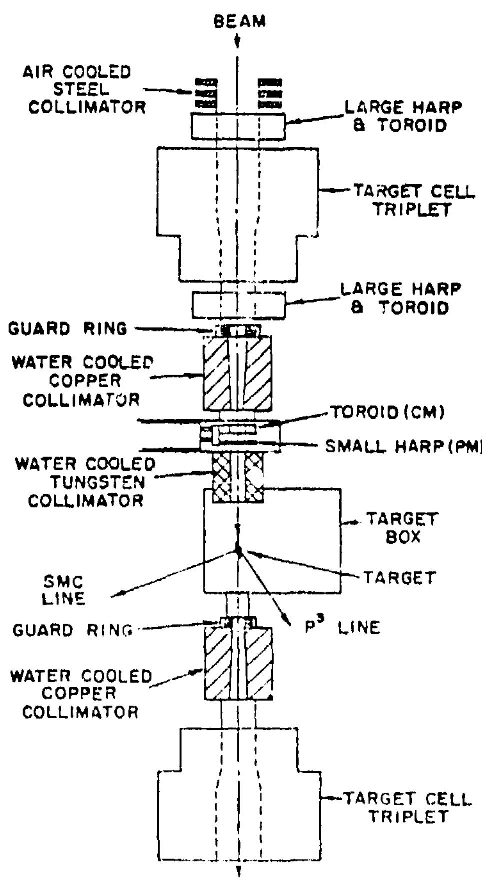

Fig. 1 - Layout of the A-2 target cell.

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All target cell components, including collimators, are designed for remote handling. Thermal cooling is an important design constraint for the collimators downstream of the targets where a normal heat load of about 25 kW is anticipated at 1 mA (for A-2). Bellows and vacuum seals are particularly difficult to cool. All collimators are equipped with thermocouples or thermal switches that are incorporated in the run permit chain. Thus, any collimator that overheats due to excessive spill or lack of cooling will not respond fast enough to prevent damage to the collimator from the normally focused full beam striking a small spot on the front of the collimator. To handle this situation, fast response scintillation detectors or guard rings are used to detect anomalous spills on the collimators and interrupt the beam via the fast protect system.

Transmission Monitor (TM)

A key element of the protection system is an accurate transmission monitor. Most of the damaging errant beam conditions produce a change in transmission that can be detected by the TM in line A. However, undetected small losses can be large enough to produce unacceptable activation in regions not accessible to remote handling.

A subset of the 15 current-measuring toroids installed along line A are used as transmission monitors. The beam line is divided into five contiguous sections across which transmission measurements are made. Three of the sections contain pion production targets; the other two are regions of hands-on-maintenance. A functional block diagram for one section is shown in Fig. 2. A toroid (CM) at the beginning and end of each section provides an accurate measure of the beam current at each point. An on-line computer (PDP-11/10) calculates the anomalous loss, $|I_2 - fI_1|$, where f is the expected fractional loss in the target, TW, and compares this with preset tolerances. If the anomalous loss exceeds the tolerance, the beam is shut off via the run permit system.

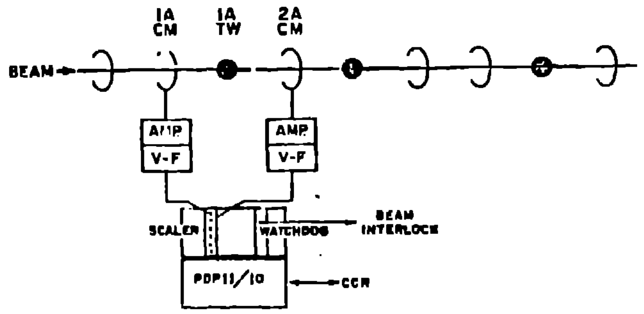

Fig. 2 - Transmission monitor block diagram.

An earlier version of the current monitoring system is described in Ref. 2. The radiation resistant toroids and data acquisition hardware are still used. In the present electronics, a single NIM-style module performs all signal-handling functions. The amplifier has a "negative resistance" input characteristic which is achieved by positive feedback on the amplifier so that the overall loop resistance, including the toroid winding, cable, and amplifier input, is close to zero. In this way the L/R time constant is made much longer than the beam macropulse width thereby eliminating variation in inductance among toroids as a factor in system response. The elimination of the time constant effects was critical in obtaining optimal performance. Each toroid has an additional single turn winding whose leads are brought out to a common line that is used to introduce calibration signals. The calibration or test procedures can be carried out from the central control computer.

The watchdog timer is a CAMAC module that must be reset every two seconds by the computer; otherwise it will time out and shut off the beam. This is to help insure that the computer program is running correctly. The frequency at which the program checks transmission is an adjustable program parameter. It is presently checked every 250 ms, and is not fast enough to prevent damage for the situation analyzed in Ref. 1.

At the present operating current of about 500 μA, the tolerance levels are typically 2 to 3 μA, which are well above the electronic noise levels. More serious noise is introduced by real variations in transmission which are correlated with rotating targets. SCR spikes, originating in magnet power supplies during the beam gate, occasionally give trouble. The credibility of the TM suffers from an annoying number of false alarms, many of which are caused by momentary fluctuations that exceed tolerance.

A hardwired TM is being developed that will have a fast response (100 μs) to very large spills as well as long integration time constants for accurate measurement of small anomalous losses. It will interrupt the beam via the fast protect system.

Secondary Emission Guard Rings

These are fast, radiation hardened spill monitors that are placed in front of collimators in the target cells and near the beam stop. They are used both for protection and diagnostic purposes. The detector shown in Fig. 3 consists of two signal planes each divided into quadrants and three high voltage planes surrounded by an isolated ground casing. The vacuum feedthrough is a Gulton Durock Hermetic TI-12-10 connector with radiation hard ($\sim 10^{15}$ rads) silico-ceramic insulation. Nickel wire, sleeved with alumina beads, is used to make the connections that are spot welded rather than soldered.

Figure 4 depicts the guard ring electronic block diagram. Electrical connection from the guard ring connector to the amplifier box is made through a fiberglass insulated cable. The signal is received at the

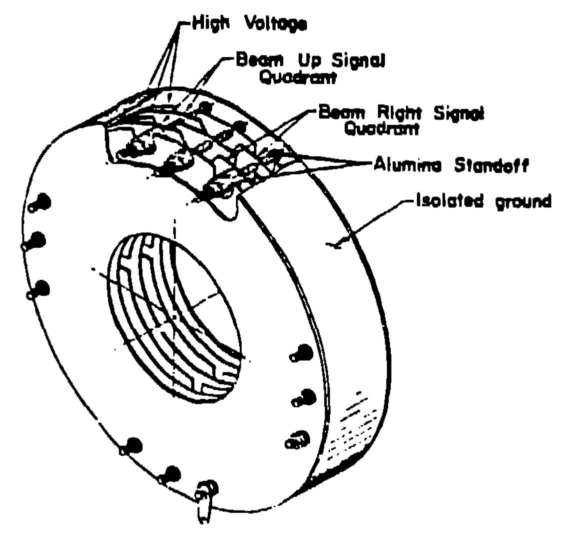

Fig. 3 - Guard ring detector assembly.

detector unit through a differential input buffer with a low pass filter. When the filtered signal exceeds an adjustable threshold, the beam is shut off via the fast protect system. The filtered signal is also digitized and used by the central control computer for diagnostic purposes. For greater reliability, the detector module also performs a self-checking function. At the end of each beam gate the HV line is pulsed and a signal, large enough to saturate the input buffers, is capacitively coupled to the signal planes. If the signal received by the detector does not exceed the threshold, then the next beam pulse is interrupted via the fast protect system.

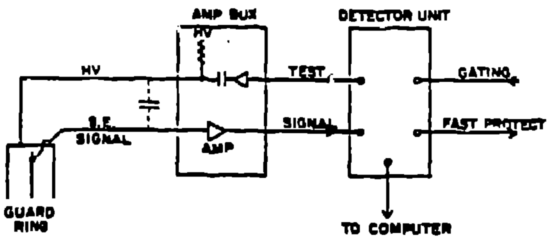

Fig. 4 - Guard ring electronics block diagram.

The operating experience with the guard ring system has been quite satisfactory. The devices are radiation hard, have a fast response time, low false alarm rate, and good sensitivity (<100 nA), for protection and even better for diagnostic purposes. The response time for the complete system, including delays in the fast protect system, is such that the beam is shut off in about 45 µs after the onset of a large spill (several times threshold). They are very specific in the sense that they directly measure the beam spill in a geometrically well-defined region. The calibration is stable since the secondary emission coefficients are fairly constant.

Unfortunately, over 40% of the guard rings have shorted out in the past three years. The apparent cause is water damage to radiation hard connector surfaces and the fiberglass insulated cables in the target cells. Replacement of the guard rings is difficult since it means replacement of the collimator to which they are attached.

Scintillation Detector Spill Monitor

A beam spill monitor and control system employing a liquid scintillation detector has been used for some time in the accelerator[3]. It is also used in low spill regions of the primary beam lines. Signals are available to monitor both peak and average spill for diagnostic purposes. Analog electronics process the signals for control of average spill via the fast protect system. Gain is adjusted by varying the photomultiplier high voltage. Calibration is done in situ by controlled spill of known amounts of beam in the vicinity of the device. This system will shut off the beam in tens of microseconds for large spills, has high sensitivity, is relatively inexpensive, but is not radiation hardened. It is not a suitable detector in the vicinity of a target or beam stop.

The A-4 tunnel is a region of beam transport between the second and third target cells in line A which is not designed for remote handling. Activation in this region is approaching levels that severely limit hands-on-maintenance. The precise origin of the halo responsible for this activation is not yet known. The scintillation spill monitor system can be set to keep the activation down but it will prevent operation at present currents. Solution of this problem for 1 mA operation will probably include additional collimators upstream of the A-4 tunnel.

Vacuum Protection

Numerous monitors of the primary beam line vacuum will shut off the beam and close valves when the vacuum system pressure exceeds acceptable values. For line A, beyond the switchyard, thermocouple gauges are set to trip at 5 to 10 X 10^{-3} torr, where harp profiles are seriously affected by residual gas ionization. Other monitors will shut off the water to the target mechanisms when the pressure exceeds 50 X 10^{-3} torr. This is done to prevent a ruptured water line from filling the vacuum system with water.

There are approximately 30 vacuum windows between the atmosphere and the line A vacuum system. Rupture of any of these windows will produce a shock and/or rush of air capable of breaking many harp wires. To provide some protection to the harps from vacuum accidents originating in the switchyard or H^- beam lines, a fast closing valve has been installed at the end of the switchyard just before the first target cell. It is a commercial device (VAT-2351VU), with a 10 cm aperture, which will close in 23 ms from the time the disturbance is detected at an upstream sensor. The device works reliably and has a low false alarm rate.

A more common cause of harp wire damage is the opening of a valve which has vacuum on one side and atmospheric pressure on the other. Where feasible, electrically operated valves are interlocked so that they can be opened only when the pressures on both sides of the valve are the same. To date, we have not lost harps to window rupture. Vacuum accidents due to human error related to opening valves have destroyed some harps. Some harp wires have been lost to lesser vacuum "incidents" of unidentified origin.

Many of the windows are at the end of secondary beam lines where the chance for window rupture increases considerably when experimenters are working near them. Valves are located upstream of the windows and are interlocked so that the valves must be closed to gain a key release for entrance to the experimental caves. The valves must also have vacuum on both sides or air on both sides in order to open.

The termination of the primary beam line consists of two 0.125 in., water-cooled Inconel windows ahead of the beam stop. The full beam, minus losses at the production target, passes through these windows. The current density must be kept small enough to avoid thermal damage to the windows. We are considering an on-line spot size monitor that will shut off the beam when the spot size falls below an acceptable value. This should be implemented before 1 mA currents are available for production.

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